Renewable and Sustainable Energy Reviews 13 (2009) 2003–2011

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# An energy analysis of ethanol from cellulosic feedstock–Corn stover

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ARTICLE INFO

*Article history:*
Received 17 November 2008
Accepted 20 January 2009

*Keywords:*
Bioethanol
Corn stover
Energy analysis
Net energy value
Co-product credits

ABSTRACT

The shift from fossil resources to renewables for energy and materials production has been the driving force for research on energy analysis and environmental impact assessment of bio-based production. This study presents a detailed energy analysis of corn stover based ethanol production using advanced cellulosic technologies. The method used differs from that in LCA and from major studies on the subject as published in Science in two respects. First, it accounts for all the co-products together and so mainly avoids the allocation problems which plague all LCA studies explicitly and other studies implicitly. Second, the system boundaries only involve the content of the energy products used in the system but not the production processes of these energy products, like refining and electricity production. We normalized the six Science studies to this unified method. The resulting values of the total energy product use in both agricultural production and biomass conversion to ethanol are lower than these literature values. LCA-type of values including energy conversion would systematically be higher, in our case study around 45%. The net energy value of cellulosic ethanol production is substantially higher than the ones of the corn-based technologies, and it is similar to incineration and gasification for electricity production. The detailed analysis of energy inputs indicates opportunities to optimize the system. This form of energy analysis helps establishing models for the analysis of more complex systems such as biorefineries.



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## 1. Introduction

Facing the threat of oil depletion and climate change, a shift from fossil resources to renewables is ongoing to secure long-term supplies, with biofuel as one of the options. Several studies on life cycle assessment (LCA) of bioenergy have been conducted, focusing particularly on two main impacts: reduction of fossil resource extraction and greenhouse gas (GHG) emissions. However, our previous studies show that LCA as a tool supporting decision-making has its limitations when multi-products are involved, requiring some form of allocation. With the upcoming biorefineries, the product systems involve variable multiple inputs and variable

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doi:10.1016/j.rser.2009.01.016

multi-outputs. Hence LCA in general cannot be applied. Therefore, an analysis methodology is needed in order to optimize integrated biorefineries with regard to energy conservation, environmental impact and profitability. Since both the environmental impact and production costs are closely related to the amount of fossil fuels used in the life cycle of a product, energy analysis can give a key insight at relatively low cost. Several studies have been conducted on the energy analysis through the life cycle of corn-based (*Zea mays*, or maize) ethanol [1–6]. Two studies stand out because they report negative net energy values [1,2], requiring more fossil energy inputs in the production processes than the energy contained in the bioethanol produced. The rest show positive net energy values to a varying extent. To permit a direct meaningful comparison of the data and assumptions across these six studies, Farrell et al. aligned methods and removed differences in underlying data. They indicate that calculations of net energy are highly sensitive to assumptions about both system boundaries and key parameter values and, as to content, conclude that large-scale use of fuel ethanol certainly requires more sustainable practices in agriculture and advanced technologies, shifting from corn to cellulosic ethanol production [7].

The cellulosic ethanol production refers to the processes converting cellulosic feedstocks (i.e. corn stover, wheat and rice straw, sugarcane bagasse, wood or grass) to ethanol. A recent paper on a comparative energy assessment of corn and stover based ethanol concludes stover is a better feedstock than corn from a perspective of energy conservation [8]. In our study corn stover was chosen as the feedstock for ethanol production. Aiming at giving an indication on the efficiency of the stover–ethanol life cycle and how to optimize the system in terms of energy production, this study focuses on an energy analysis providing an overview of the total use of energy products, in all (sub-) processes or sections of the stover–ethanol life cycle. The results are used for comparison between different systems and optimization of the corn agriculture and the fuel ethanol production.

## 2. Methodology

### 2.1. System boundary and allocation

All relevant processes in the biomass production (corn agriculture producing corn and stover) and the conversion to ethanol are included within the system boundaries of the ethanol life cycle, as shown in Figs. 1 and 2. Capital goods production and wastes management are also included. It is not a 'cradle-to-gate' system, as usual in LCA, but an 'energy products-to-gate' analysis, Primary energy conversion processes have been left out of account, though an overall comparison is made to show the quantitative effect of this exclusion.

There is no allocation involved in the foreground processes, as all co-products are included there, making the outcomes independent of arbitrary allocation choices which otherwise would have to be made. Implicitly, allocation is involved in the data used for the background processes, with a limited quantitative effect on outcomes however. As there is no allocation, the systems compared involve differing amounts of the four main products: corn, stover, electricity and ethanol.

In order to make comparisons, we analyze these co-products from an energy content point of view. Other measures might be used, like economic value, adding broadness but not requiring other types of modeling. Adding specific applications of corn, stover, ethanol and electricity will surely lead to different outcomes of such more application focused studies. We leave these out of account here, but they could easily be added.

For the sake of simplicity, environmental effects have been left out of account as well, focusing on energy only. In the modeling framework as applied, such effects can be specified in the usual ways as have been developed in the realm of LCA.

### 2.2. Data sources

Data used in this study are obtained from different sources. U.S. Life-Cycle Inventory Database [9] is the main source for agriculture data, and the data from Swiss Centre of Life Cycle Inventories (Ecoinvent) [10] are used for adjustment when necessary. Data on transport of stover, ethanol and electricity production are from NREL report [11].

### 2.3. Energy analysis

#### 2.3.1. Comparison with literature values

In order to compare the results with literature values, the energy use in corn agriculture is calculated on a 'per hectare' basis for 14 cost categories. The crop yield taken in this study is 8687 kg corn/ha [12], which means the annual yield of the harvested stover is 5112 kg/ha [13]. In the other studies these data are slightly different and mostly stover is not specified. The total energy input in ethanol production is calculated based on producing 1 L of ethanol. Although the ethanol is produced from stover instead of corn, the results can provide an

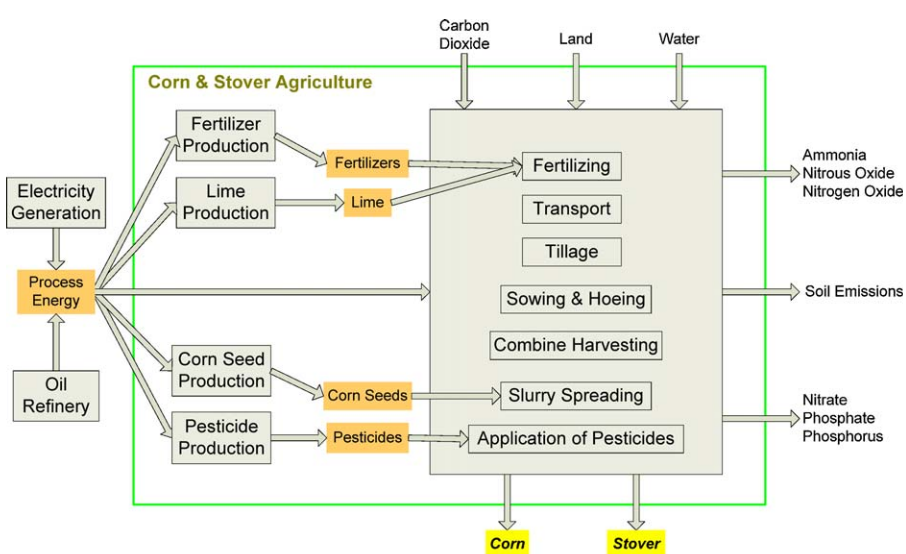



**Fig. 1.** Corn and stover agriculture.

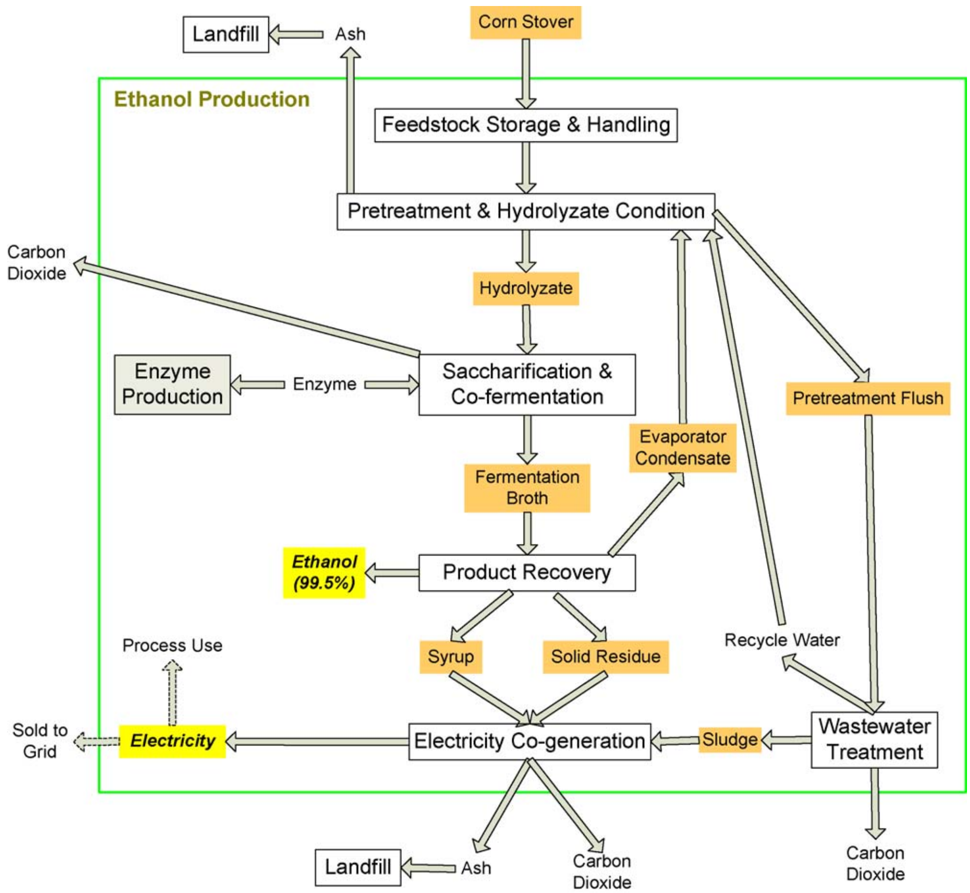



**Fig. 2.** Ethanol production from stover.

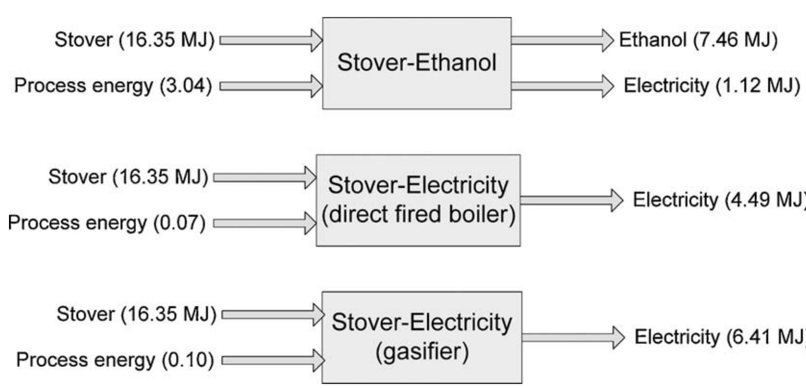



**Fig. 3.** The defined comparable systems.

indication on the scale of values, and more importantly, how efficient cellulosic technologies are as compared to corn based ethanol. Furthermore, net energy values without and with co-product credits were calculated and compared the literature values. In the case of ethanol production from stover, electricity is the only co-product from the biorefinery.

*2.3.2. Calculations of energy inputs*

In order to find out the energy intensive sub-processes and improve process efficiency, a detailed analysis was performed. The calculations of energy inputs are based on the production of 1 kg of ethanol, which requires 3.97 kg of stover, while 6.62 kg of corn is co-produced in agriculture. The agriculture process is divided into two sections—production of agriculture inputs and agricultural production. When producing 1 kg of ethanol, 1.23 kWh of electricity is co-generated. All the sub-processes are indicated in Figs. 1 and 2.

## 3. Results and discussion

### 3.1. Results of energy use

The results of energy use in corn agriculture and the total energy use in ethanol production compared to the literature values are shown in Tables 1 and 2, respectively.

It can be seen from Table 1 that the total energy use in agriculture is in the same scale as the values in the literature, although it lies on the low side. The major differences appear in

**Table 1**
Comparison of energy use in corn agriculture with literature.

| | This study | [1] Patzek | [2] Pimentel | [3] Shapouri | [4] Graboski | [5] de Oliviera | [6] Wang |
|---|---|---|---|---|---|---|---|
| Corn production (kg/ha) | 8,687 | 7,310 | 8,655 | 8,746 | 8,799 | 7,850 | 7,846 |
| Stover harvest (kg/ha) | 5,212 | – | – | – | – | – | – |
| Energy use in corn agriculture (MJ/ha year) | | | | | | | |
| Fertilizer production | 7,988 | 9,160 | 12,431 | 9,804 | 8,077 | 8,681 | 10,305 |
| Lime production | 1,067 | 583 | 1,318 | – | 369 | 445 | – |
| Pesticide production | 197 | 953 | 3,766 | 1,060 | 777 | 1025 | 970 |
| Seed production | 158[a] | 1,968 | 2,176 | 228 | 215 | 2,048 | – |
| Transport | 398 | 400 | 707 | 73 | 738 | – | 168 |
| Gasoline | – | 1,005 | 1,695 | 1,277 | 1,290 | 960 | 1,501 |
| Diesel | 3,071[b] | 2,957 | 4,197 | 2,719 | 3,205 | 2,907 | 4,310 |
| LPG | – | 1,205 | – | 765 | 1,357 | 1,512 | 1,072 |
| Natural gas | 116[c] | 779 | – | 670 | 597 | 504 | 1,626 |
| Electricity | 382 | 688 | 143 | 820 | 1,571 | 657 | 225 |
| Irrigation | – | – | 1,339 | 49 | – | – | – |
| Labour | – | 1,390 | 1,934 | 574 | 628 | – | – |
| Farm machinery | 3,249[d] | 6,050 | 4,259 | – | 320 | – | – |
| Input packaging | – | – | – | – | 74 | – | – |
| Total | 16,626 | 27,138 | 33,954 | 18,041 | 19,220 | 18,738 | 20,177 |

[a] This value was taken from Ecoinvent database, as it is not provided in the U.S. database.
[b] In the U.S. database, gasoline and LPG are used together with Diesel for the operation of agricultural machinery. However, Ecoinvent database was used to calculate the energy inputs in all the agricultural operation, where only diesel is used as fuel.
[c] Also calculated from Ecoinvent database.
[d] Calculated by this study, as it is not provided in the U.S. database.

**Table 2**
Comparison of total energy use in ethanol production.

| Energy use in ethanol production (MJ/L) | This Study | [1] Patzek | [2] Pimentel | [3] Shapouri | [4] Graboski | [5] de Oliviera | [6] Wang |
|---|---|---|---|---|---|---|---|
| Total | 9.5 | 17.0 | 17.0 | 15.2 | 16.6 | 14.1 | 12.5 |

pesticide production, gasoline and LPG consumption. Since the U.S. database only provides the total amount of pesticides used without specifying the energy type of herbicides and insecticides and the energy needed to produce the pesticides, the Ecoinvent database was used to estimate the energy engaged in the production, which can be somewhat optimistic. In the U.S., it is common to use gasoline and LPG together with diesel for the operation of agricultural machineries. However, in Ecoinvent database the fuel for agriculture operation is mainly diesel, and total fuel consumption was lower than the data from the U.S. database. The major reason why the U.S. life-cycle inventory database was used together with Ecoinvent database is to obtain a summary of energy inputs in all the sub-processes in the agriculture, as shown in Section 3.2.

For the total energy use in the stover based ethanol production, it takes 9.5 MJ of process energy to produce 1 L of ethanol. Although the pretreatment of cellulosic feedstock is highly energy intensive, the value of energy use is low compared to the literature values for ethanol from corn. The reason for this result might be that we assumed the process to be highly optimized in terms of energy efficiency. Due to the incompleteness of the data in sub-processes in ethanol production provided by the literature, only the values of the total energy use can be compared. Nevertheless, this gives an indication on how efficient the cellulosic process is. The net energy summaries compared to the literature values is shown in Tables 3 and 4.

The results show that when the co-products are not taken into account, three literature studies results in a negative net energy value. When the co-products are taken into account, all six studies give positive net energy values. This indicates that outcomes of net energy calculations depend on taking into account the energy value of co-products. Farrell et al. only reckon with the co-products from biorefinery, and not the stover produced from agriculture. In our study all the co-products are included, also for the six literature studies [1–6].

The reason why the energy use per liter of ethanol in our study is the highest is that the yield of ethanol from stover is lower than the one from corn. In order to produce 1 L of ethanol more stover is needed. While in our study the energy use for the biomass conversion processes is substantially lower, due to its advanced nature. In this study, the net energy value is much higher mainly due to the co-product of corn, which is consumed in the ethanol production of the first generation to which the other studies refer. Although the average ethanol yields in the six studies is 0.4 L

**Table 3**
Net energy summary excluding co-products, no allocation.

| Energy Use (MJ/L) | This Study | [1] Patzek | [2] Pimentel | [3] Shapouri | [4] Graboski | [5] de Oliviera | [6] Wang |
|---|---|---|---|---|---|---|---|
| Agriculture | 10.0 | 9.9 | 10.0 | 5.3 | 5.6 | 6.3 | 6.6 |
| Biorefinery | 9.5 | 17.0 | 17.0 | 15.2 | 16.6 | 14.1 | 12.5 |
| **Total input** | **19.5** | **26.9** | **27.0** | **20.5** | **22.2** | **20.4** | **19.1** |
| Ethanol[a] | 21.2 | 21.2 | 21.2 | 21.2 | 21.2 | 21.2 | 21.2 |
| **Total output** | **21.2** | **21.2** | **21.2** | **21.2** | **21.2** | **21.2** | **21.2** |
| **Net energy value** | **1.5** | **−5.7** | **−5.8** | **0.7** | **−1.0** | **0.8** | **2.1** |

[a] Normalized energy value for ethanol based on lower heating value (LHV).

**Table 4**
Net energy summary including co-products, no allocation.

| Energy use (MJ/L) | This study | [1] Patzek | [2] Pimentel | [3] Shapouri | [4] Graboski | [5] de Oliviera | [6] Wang |
|---|---|---|---|---|---|---|---|
| Agriculture | 10.0 | 9.9 | 10.0 | 5.3 | 5.6 | 6.3 | 6.6 |
| Biorefinery | 9.5 | 17.0 | 17.0 | 15.2 | 16.6 | 14.1 | 12.5 |
| **Total input** | **19.5** | **26.9** | **27.0** | **20.5** | **22.2** | **20.4** | **19.1** |
| Ethanol[a] | 21.2 | 21.2 | 21.2 | 21.2 | 21.2 | 21.2 | 21.2 |
| Co-products in agriculture[b] | 85.2 | 25.9 | 25.9 | 24.0 | 24.6 | 24.6 | 24.6 |
| Co-products in biorefinery[c] | 3.5 | 4.1 | 1.9 | 7.3 | 4.1 | 4.1 | 4.0 |
| **Total output** | **109.9** | **51.2** | **49.0** | **52.5** | **49.9** | **49.7** | **49.8** |
| **Net energy value** | **90.4** | **24.3** | **22.0** | **32.0** | **27.7** | **29.3** | **30.7** |

[a] Normalized energy value for ethanol based on lower heating value (LHV).
[b] In this study it refers to the corn as a co-product in the agriculture; in all the other six studies it refers to the harvested stover (60%, dry mass basis) as a co-product, and the values are estimated in this study.
[c] In this study it refers to electricity; in the literature studies it refers to a range of products from corn milling, such as dried distiller grains, corn gluten feed, corn oil, etc.

**Table 5**
Energy input, output and net energy values of the applications of stover.

| Defined system | Process energy use (MJ/kg stover) | Electricity generated (MJ/kg stover) | Ethanol produced (MJ/kg stover) | Net energy value (NEV)[a] (MJ/kg stover) |
|---|---|---|---|---|
| Stover–ethanol | 3.04 | 1.12 | 7.46 | 5.54 |
| Stover-electricity (direct fired boiler) | 0.07 | 4.49 | – | 4.42 |
| Stover-electricity (gasifier) | 0.10 | 6.41 | – | 6.30 |

[a] Net energy value (NEV) = ethanol produced + electricity produced − process energy use.

ethanol/kg corn, while in our study the yield is only 0.3 L ethanol/kg stover, cellulosic ethanol is more energy efficient. Moreover, it can be seen that co-generation of electricity from wastes is a way to increase energy efficiency.

One further question may then be raised, 'Is it better to use stover for ethanol production or just burn it for power generation?' In order to answer this, two reference systems were defined to generate electricity, incinerating the same amount of stover as required for the production of 1 kg of ethanol, that is 63.5 MJ (3.97 kg) of stover. The energy use and the electricity generated in this system were calculated. The systems in comparison with the stover–ethanol system are defined in Fig. 3 and the results are shown in Table 5.

Table 5 shows that in terms of net energy generation the benefit of converting a given amount of stover to ethanol stands in between the ones for power generation from two electricity options, disregarding the further use of end products, here only ethanol and electricity. The energy cost for stover–ethanol and electricity production is higher, but so are its energy proceeds. If the application of ethanol and electricity is considered, the efficiency of ethanol use may be much lower than the one of electricity use, as combustion process have a low energy efficiency score. Also the possibility of using low temperature steam for urban heating is not specified here. Creating more valuable products from lignocellulosic biomass than only energy seems a promising option as well however, but then leaving the domain of energy product analysis. With further optimization of the ethanol production process, higher net energy value can be achieved.

## 3.2. Survey of energy inputs

The energy inputs in different sub-processes (sections) in agriculture and in ethanol production are shown in Figs. 4 and 5, respectively. The lower heating value (LHV) is the basis for the energy production analysis.

In Fig. 4 the total energy use given (12646 kJ) refers to the sum of the energy content of the fuels used in agriculture, but not the primary energy—the energy sources (i.e. crude oil, coal, uranium, biomass, etc.) in the oil refinery and electricity production processes. This system boundary is different from the one in life cycle assessment (LCA), which is 'cradle to gate'. As we want to compare the results in this study with the literature values, the choice of the system boundary is also consistent with the one in the literature studies.

How do our scores relate to the LCA-type cradle-to-gate outcomes, with an expanded system definition? When the values of the total energy input in the refinery and electricity production are used instead of only the ones of the energy outputs, the embodied energy is added to these flows. In this case the total energy use in agriculture becomes 18,394.49 kJ for the production of 6.62 kg of corn and 3.97 kg of stover. The summary of the energy use from the two comparable system definitions is given in Table 6.

The reason why the value for the biorefinery does not differ in the two cases is that the energy use (mainly steam and electricity) is supplied by the heat and power production within the refinery. Hence no external energy source is needed.

In the corn-stover agriculture, fertilizer production, tillage and harvesting are the most energy intensive processes. The reason why fertilizer production contributes most to the energy use in agriculture is the large amount of natural gas used for steam reforming in the production of ammonia, which is then used in the production of nitrogen fertilizers. Tillage and harvesting require a large amount of diesel, which is needed for the operation of agricultural machineries.

In Fig. 5 the total electricity consumed is 4217 kJ/kg ethanol, and the co-generated electricity is 4433 kJ/kg ethanol. This corresponds to the number 1.12 MJ/kg stover in Table 5, which is not expressed per liter ethanol but per kg stover. The surplus of 216 kJ can be sold to the grid. In the ethanol production, the causes of the large energy inputs in pretreatment, product recovery and enzyme production are the steam and electricity used. Steam is needed for stover pre-hydrolysis due to the high temperature requirement in hydrolysis reactor, and for condensation and the preparation of the boiler feed water. Since aerobic fermentation is used in the enzyme production, electricity is used to pump air into the fermenter continuously.

After all the bottlenecks in the ethanol life cycle are defined, possible solutions are provided as follows for process optimization to reduce energy consumption.

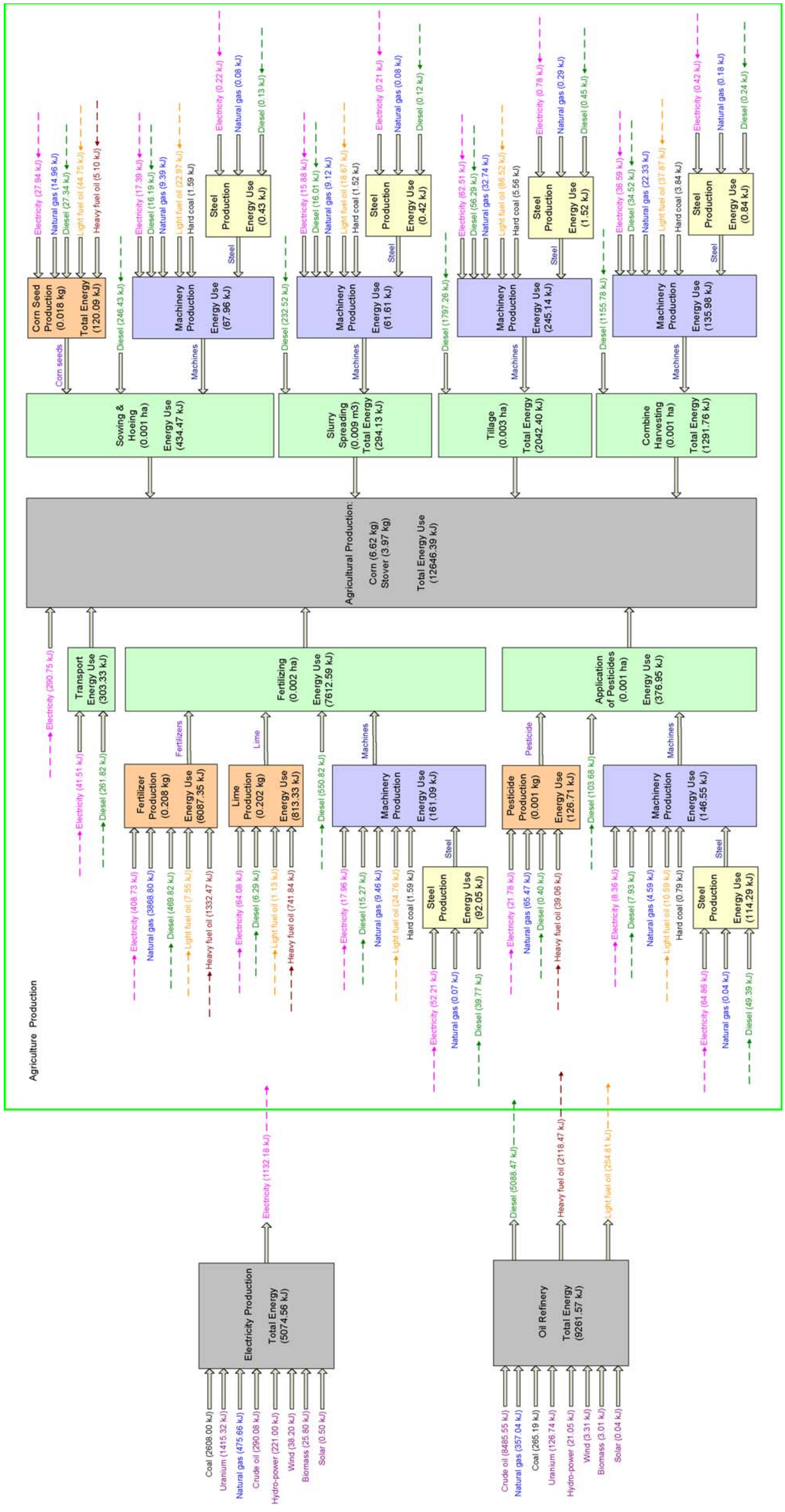



**Fig. 4.** The energy inputs in corn-stover agriculture (unallocated).

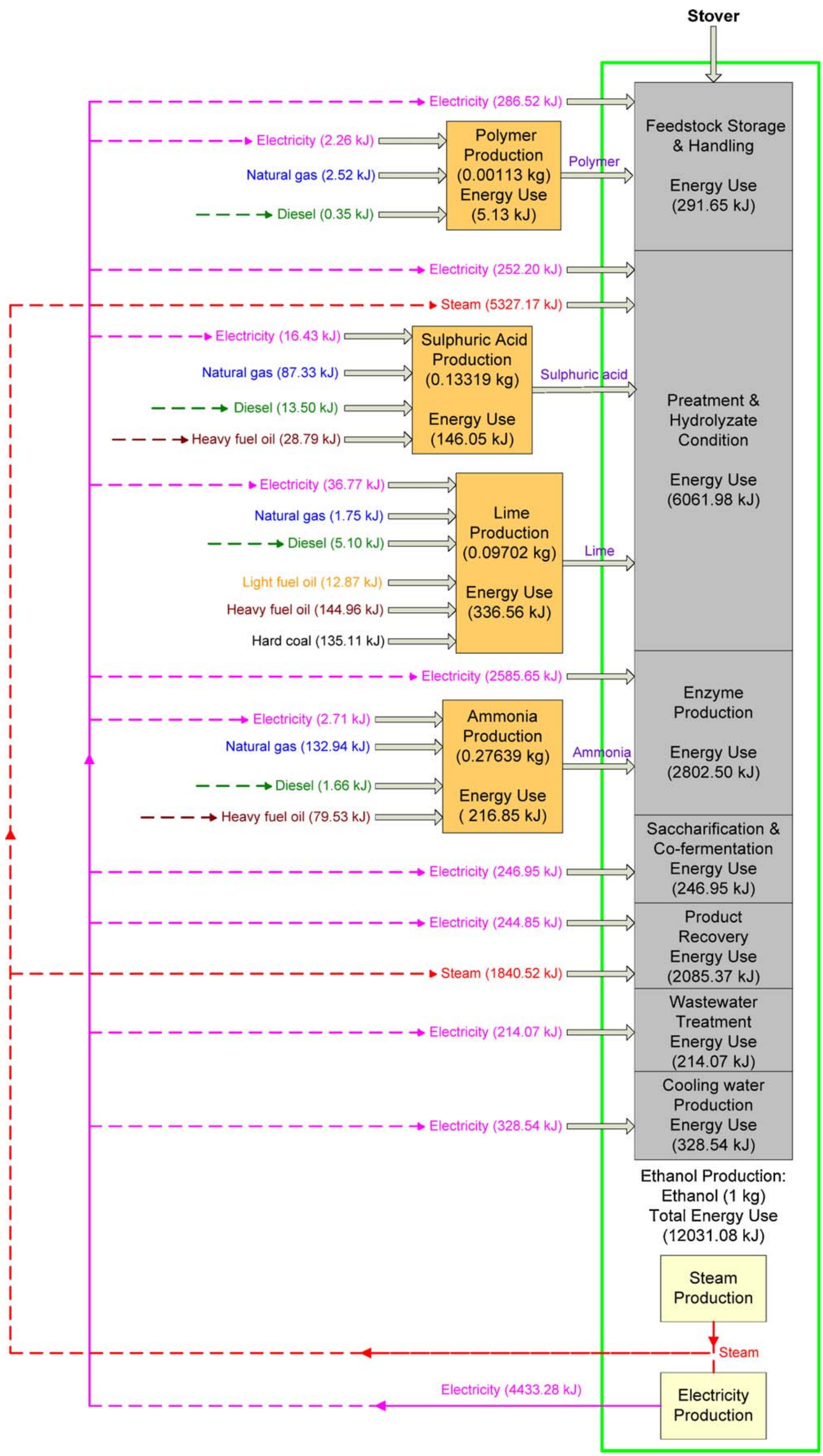



**Fig. 5.** The energy inputs in stover biomass conversion to ethanol (unallocated).

**Table 6**
Energy use in cradle-to-gate and in energy-product analysis.

| Energy use | Methodology | |
|---|---|---|
| | Cradle-to-gate (MJ/kg ethanol) | Energy-product (MJ/kg ethanol) |
| Agriculture | 18.39 | 12.65 |
| Biorefinery | 12.03 | 12.03 |
| Total | 30.42 | 24.68 |

- To produce ammonia by nitrogen fixation instead of steam reforming;
- To increase engine efficiency of the agricultural machines to reduce the fuel use;
- To use less energy intensive crops like sugarcane or grass instead of corn stover;
- To use non-thermal methods for pre-treatment, i.e. chemical or mechanical methods;
- To increase boiler efficiency of the distillation and rectification columns;
- To apply anaerobic fermentation for cellulase production to prevent aeration.

All the aforementioned means of improvement have their own limitations comparing to the technologies engaged in the present study. For instance, nitrogen fixation might be more costly than steam reforming; investment and initiatives need to be made to increase the efficiency of machineries; the supply of different feedstocks depends on its regional availability and cost for transport; the application of anaerobic fermentation might bring the yield of cellulase down. With all the incentives in reducing energy consumption and the limitations mostly in process economy, technology development shall be further investigated.

## 4. Conclusions and recommendations

This study presents a detailed energy analysis of stover based ethanol production using advanced cellulosic technologies. Unlike the 'cradle to gate' approach in LCA methodology, the system boundaries defined in the present study as well as in the literature we compared our results with, only involve the energy content of the energy product but not the energy inputs to the production processes of these energy products. Furthermore, for the calculation of net energy values, all the six studies as well as Farrell's study only reckon with the co-products from biorefinery but ignore the ones from agriculture, in their case stover. In this study this has been corrected. The resulting values of the total energy use in both agriculture and ethanol production are lower for the case of stover based ethanol than the ones for corn based ethanol production. In the corn agriculture the low energy use is mainly due to lower fuel use in the operation of agriculture machineries. The reason for this is that, the data provided by the U.S. Life-Cycle Inventory Database have been optimized. In the second generation stover–ethanol production, the much lower total energy use is due to the highly optimized process design in terms of energy efficiency. When all the co-product are taken into account, the net energy value becomes much higher than the literature covering the corn cases, which shows ethanol production from cellulosic feedstocks is more energy efficient than corn-based ethanol. Moreover, co-generation of electricity from wastes is an important way to increase energy efficiency in the cellulosic ethanol process.

The survey of energy inputs indicates the bottlenecks in the ethanol production chain—fertilizer production, tillage and harvesting in the agriculture, and pretreatment, enzyme production and product recovery in the biorefinery. The detailed investigation of the energy inputs in all the energy intensive processes provides the opportunity to optimize the system in terms of net energy production.

The production of nitrogen fertilizer consumes more than 90% of the energy in fertilizer production, thus the possibilities of reduction of nitrogen fertilizer use and improved production processes require attention. For instance, organic farming replacing synthetic fertilizers by green manure may result in less energy use and lower environmental impact. Concerning agriculture processes, optimization should focus on the design of the machineries in order to achieve higher efficiency to reduce fuel consumptions. Furthermore, stover might not be a good feedstock option for cellulosic ethanol production due to its highly intensive agriculture. More promising feedstocks can be sugar cane and switchgrass.

In the ethanol production, advanced technologies involving two steps pretreatment (dilute acid prehydrolysis and enzymatic saccharification) and genetically modified organisms (GMO) for fermentation are engaged. The process has been conceptually designed and optimized in terms of production yield and energy efficiency, but yet it needs to be established in practice. To further optimize the system, strain development of microorganism to achieve a high yield and innovations of pretreatment and recovery options can be the focus. It is worth noting the goal of energy conservation may bring side effects such as worse environmental performance, low profitability or unacceptable options by the society. Therefore, it is crucial to develop a model for optimization with a complete set of criteria, among which a reduced input of energy products can be an important one.

The present study also indicates that in terms of net energy value created, the incineration or gasification of cellulosic feedstocks is not better than ethanol and electricity production. There are opportunities to further increase the value derived from biomass processing by coproducing high valued products next to ethanol, especially using agricultural wastes as are available in varying compositions. In such a complex multi-feedstocks and multi-products biorefinery system, the production of high volume of low-value products (like fuels) and low volume of high-value co-products (like pharmaceutical precursors) can be combined. Together with collective feedstock supply, waste treatment and integrated power generation, a biorefinery complex could potentially maximize the total value derived from cellulosic feedstocks and minimize the energy consumption and environmental impacts.

## Acknowledgements

This project is financially supported by the Netherlands Ministry of Economic Affairs and the B-Basic partner organizations (http://www.b-basic.nl) through B-Basic, a public-private NWO-ACTS program (ACTS = Advanced Chemical Technologies for Sustainability).

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